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by

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J. Schröter

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Procurement Executive, Ministry of Defence
Farnborough, Hants

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MECHANICAL IMPEDANCE OF THE HUMAN OUTER EAR

(MECHANISCHE IMPEDANZEN AM AUSSEREN OHR DES MENSCHEN)

by

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EDITOR'S SUMMARY

The current lack of a quick, cheap and accurate method of measuring the attenuation provided by hearing protectors has hampered the development of these devices. Many efforts to provide such a method have involved the design of an objective test apparatus or 'artificial head'. A major drawback to this solution has been the lack of detailed information about the mechanical characteristics of the skin/flesh layer at the point of contact between the protector and the head of a wearer.

This paper describes the measurement of the mechanical impedance of the skin/flesh layer of 100 subjects at four points in the circumaural region and at a point in the outer ear canal. The application of these data to the design of an artificial skin/flesh layer for use on an 'artificial head' is discussed.

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Figures 3/1-2, 4/1-22

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Part 1

1 MOTIVATION AND AIM OF WORK

During the construction of an artificial head for the measurement of sound attenuation of ear protectors, it is necessary to simulate the mechanical properties of the layers of skin on which the ear protector lies. A relevant factor here is the dynamic behaviour of layers of human tissue as characterised by their mechanical impedance. This is defined as the complex ratio of the Fourier transform of the force and velocity at a test point.

Before the test involving simulation of human skin is carried out, it is first of all necessary to know its properties, ie its mechanical impedance. The aim of the work was to investigate these original data. Moreover, with the help of statistical methods, an attempt was made to ascertain whether, and to what extent, the individual data could be combined to give characteristic mean values.

2 TEST METHOD AND TEST STRUCTURE

A detailed description of the test structure and of the test method has been given by Schröter and Els (1979) so that only a rough summary need be given here.

Measurements were carried out of the force and acceleration at definite points, a vibration exciter being used to produce mechanical vibrations. The mechanical impedance was calculated from the two signals with the aid of a laboratory computer. The test structure essentially resembles that described in the reference cited above. Only the suspension of the vibration exciter was changed. It was now secured to a beam balance, by which the necessary small bearing force could be established considerably more accurately than with the original arrangement.

3 TEST PARAMETER AND TEST PERSONNEL

The mechanical impedances were recorded at four points for each test person, these points being distributed around the pinna (Fig 3/1) and were also determined for the layers of tissue in the outer canal of the ear.

Mechanical vibrations were transmitted to the tissue layers of the test points around the ear by means of a flat, circular aluminium punch (area 1.75 cm^2). The static pressure applied by the punch to the test point is about 0.2 N ($0.25 \text{ N} \pm 0.01 \text{ N}$) and 0.5 N ($0.46 \text{ N} \pm 0.01 \text{ N}$). At test point 3 (mastoid), an additional measurement was made at 5.4 N. The lower pressures applied result in roughly the force which is exerted by capsule-type ear protectors; if such a protector, having an area of about 50 cm^2 , is associated with a force of 10 N, this would correspond to a pressure which would be exerted by the punch used here at a force of about 0.35 N.

As a result of the natural instability of movement of the test person, changes occur in the static pressure. Due to the small values of the forces involved, this leads to larger relative errors than in the case of measurements at higher bearing forces. However, the force and acceleration signals obtained in each case had a periodic pattern and were therefore averaged over 400 periods (within a test time of about 30 s), before being processed by the computer to give an impedance. In this way, the bearing forces mentioned above could, on average, be realised.

In order to determine the shear impedance of the walls of the ear canal, two aluminium punches, initially forming the frustum of a cone, were used. The smaller varied in external diameter from 5 mm at the tip to 9 mm over a length of 10 mm; the external diameter of the larger cone was 7 mm at the tip and 10 mm further up at a height again of 10 mm. The test person concerned himself introduced the appropriate punch into the auditory canal. The beam of the balance was then almost at equilibrium with a small excess weight on the side carrying the vibration exciter. The test person was instructed to insert the punch into the auditory canal until it sat as firmly as an ear protector plug of soft plastic. From earlier measurements, it had been established that it was not possible to achieve an objectively defined pressure of the surface of the cone mantle applied to the wall of the auditory canal by way of the static force with which the vibration exciter-punch arrangement was pulled downwards. Therefore, in this series of tests, the force of the pressure was established subjectively.

The measurements afforded impedance values for 208 equidistant frequencies from 100 Hz to 10 kHz.

100 test persons were used and 10 measurements were carried out on the right side of each head. That is, one measurement at each test point 1-4 and at each bearing force (0.2 N, 0.7 N), plus one measurement at test point 3 using a static pressure force of 5.1 N and one measurement of the impedance at the wall of the auditory canal. The persons tested included 35 females and 65 males. The age distribution is shown in Fig. 3/2. In addition, the corresponding impedances were measured on the left side of the head in the case of 10 test subjects, in order that a right-left comparison could be carried out.

The reproducibility of measurements was ascertained by repeating each individual measurement on a test person five times. The test arrangement was newly applied to the test point on each occasion.

4 EVALUATION

Of particular interest where circumaural mechanical impedances are concerned is the frequency range below 2 kHz. As has already been shown (Schröter and Els, 1979), the sound damping of a capsule-type ear protector from about 1 kHz is determined only by its mass; above 1 kHz therefore, the effect of the skin is negligibly small.

The reproducibility of results in the case of measurements at the same test point and on the same test person was, in part, good; however, at many test points, the scatter achieved values of an order of magnitude approached by inter-subject deviations. For the relevant low and medium frequencies, two physiological circumstances were, above all, responsible for the worsening of the reproducibility: hair between the punch and the skin, and also the relatively round bones with thin tissue covering. In these cases, hope could almost be excluded of positioning the punch in the same way at all applications; test values obtained for such points showed correspondingly wide scatter. The relative standard deviations could then attain values of up to 25% (test point 2, 0.2 N bearing force; hair!). Typical curves are shown in Fig. 4/1 and 4/2.

For measurements of the wall impedance of the auditory canal, in spite of the poorly-defined application force of the punch, good reproducibility of data was achieved (Fig. 4/3).

The relative standard deviation in this case was less than 5%. For reasons already mentioned (non-linear distortions of the vibration exciter, see Schröter and Eis 1979), these measurements could be carried out only in the frequency range up to 4 kHz. As shown in this same article, however, this was quite adequate, since, above 4 kHz, again the sound damping is determined only by the mass of an ear plug. Using data obtained on 10 test subjects, a right-left comparison was carried out in order to see whether any differences existed between test values for the right and those for the left ear. These tests were accomplished by means of the F-test for variances and t-test for mean values (significance level $\alpha = 0.05$) (Sachs 1978). No significant differences were found for the circumaural measurements in the frequency range of interest up to at least 1 kHz.

In order to assess the dependence of the impedance on the age or sex of the test person, mean values were first of all calculated over a group separated according to sex and age, whereupon three age groups were defined: II: 16-25 years; III: 26-35 years; IV: more than 35 years (see also Fig 3/2). Male and female test persons under 16 years of age formed a further group, I.

Arithmetical means of the real and imaginary parts were calculated. Test persons whose R-test data (Nalimov 1963) recognised as strays ($\alpha = 0.05$) were not included.

The mean values thus obtained failed to show any tendencies as regards dependence on age within the scatter of values. No significant conclusions concerning age dependence could be established on the basis of a simple variance analysis either. Division into age groups was therefore abandoned and the mean values within the male and female groupings were combined (Fig 4/4 to 4/13).

The curves of these new mean values lead to the assumption of differences between impedances of male and female test subjects initially only in the case of test point 2. In fact, the F- and t-tests support this assumption. From about 1 kHz, the reactances differ significantly ($\alpha = 0.05$). The greater pliability encountered for females can be attributed to their thicker growth of hair at this point.

Values for the remaining test point appear to show no further clear differences. However, it was only for test point 3 that no difference was established according to F- and t-tests ($\alpha = 0.05$).

At test point 1, significant differences for the reactance at low frequencies were obtained at low frequencies ($\alpha = 0.05$). At high frequencies (>6 kHz) and 0.2 N force of pressure, it was no longer possible to carry out the t-test, since the F-test there indicated different variances of the basic overall resistance. This can be attributed to the fact that the physiological properties at this test point vary greatly. The thickness of the layers of tissue under the skin particularly showed wide inter-individual differences at this point. Especially at the small bearing forces prevailing when the punch is not so deeply pressed in, very variable tissue thicknesses are encountered.

At test point 4, it was possible to detect differences in the reactance and resistance at low frequencies ($\alpha = 0.05$). In the case of frequencies above about 4 kHz, no t-test could be carried out, due to the widely differing variances. For this test point also, the remarks made above are valid.

No difference could be detected between male and female test subjects where the impedance of the wall of the auditory canal was concerned. The mean impedance at test point 3 for a bearing force of 5.4 N was comparable with more recent results of other authors (Fig 4/12). A striking feature is the fact that the mean values of the impedance measured here show no resonance, so that the mass component is obviously missing. An explanation of this is that, in the case of some of the test persons, measurements were carried out not directly on the mastoid but under an intermediate layer of hair. The large spring component which then occurs at high frequencies led to the apparent disappearance of the mass component from the mean values recorded.

Finally, the mean values for all test persons together were obtained. It was found (Fig 4/14 to 4/17) that the increase in the static bearing force at test points 1-4 is, on average, accompanied by an increase in the skin resistance and by a decrease in the elasticity of the skin.

The tissue, perhaps with overlying hair, behaved, at points 2 and 3, like a spring subject to losses. At test points 1 and 4, a mass component additionally occurred. The rather thicker layers of tissue there vibrate, in certain frequency ranges, as an inert mass, ie as a whole.

The standard deviations associated with these mean values are presented in Fig 4/18 and 4/19. Their relative value was on average about 50%. However, considerably smaller or larger standard deviations were sometimes found. The larger values arose from the fact that for the small static pressure forces, inter-individual differences in the skin thickness and quality and also in the hair growth affect the skin impedance to a much greater extent than they do for higher bearing forces.

A comparison of the impedances at different test points for the same application force (Fig 4/20 and 4/21) shows the scatter of the mean values between these points.

The values shown in Fig 4/22 were obtained for the mean impedance of the auditory canal (the peak in the resistance curve at 300 Hz can be explained by non-linear distortions produced by the vibration exciter). The walls of the auditory canal behave, in the frequency range considered, like a spring subject to losses. The large standard deviations can, largely, be attributed to the fact that the adjustment of the punch in the auditory canal was carried out by the test person concerned, and that therefore the pressure forces and areas established varied greatly from one test person to another.

5 CONCLUSION

The mechanical impedance was measured at four circumaural test points and in the outer auditory canal of 100 test persons. The static pressure forces were of similar order of magnitude to those produced by appropriate ear protectors.

No difference could be established in impedance values for the right and the left side of the head.

Similarly, no significant variations in impedance with age could be found.

Differences between impedance values for female and male test persons are sometimes present. In the relevant frequency ranges, however, these are so small that their value

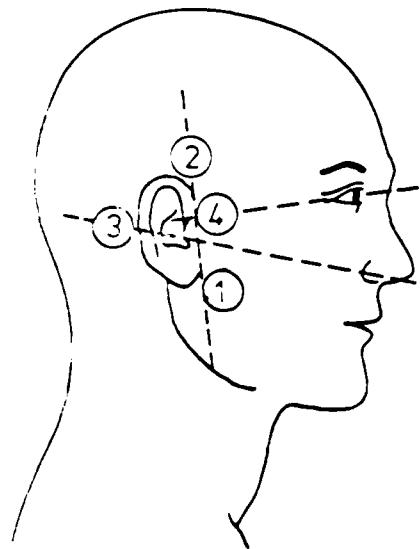
is too small, in comparison with the scatter range of test values, to serve as a representative quality of the basic totality.

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<u>Author</u>	<u>Title, etc</u>
G. Flottorp	Mechanical impedance of human headbones (forehead and mastoid portion of the temporal bone) measured under ISO/IEC conditions.
S. Solberg	JASA, <u>59</u> (1976) 899-906
V.V. Nalimov	The application of mathematical statistics to chemical analysis. Oxford, London, Paris, Frankfurt, 1963
U. Richter	Neuere Untersuchungen über die mechanische Impedanz der Stirn und des Mastoids. (More recent investigations into the mechanical impedance of the forehead and mastoid)
K. Brinkmann	5th Conference on Acoustics, Budapest, 1973
L. Sachs	Angewandte Statistik. (Applied statistics) Berlin, Heidelberg, New York, 1978
J. Schröter	Die akustischen Eigenschaften des Hauerkörpers. (The acoustic properties of the human head)
H. Els	Research project 223. 214-363 of the Bundesanstalt für Arbeitsschutz und Unfallforschung, Dortmund (1979)

W.W.M.

Fig 3.1



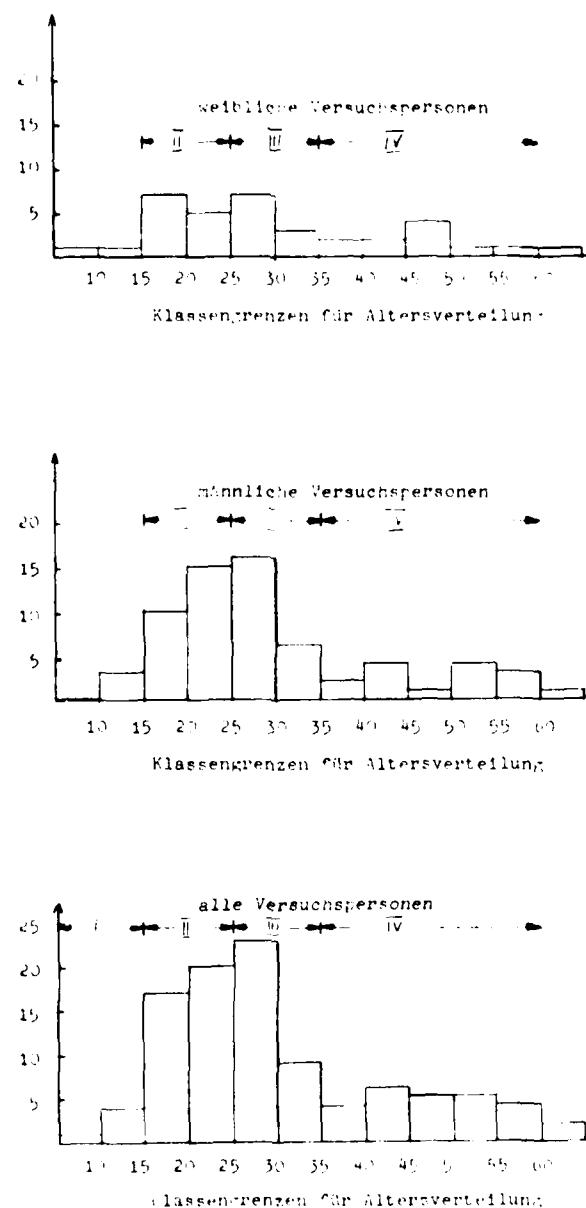
- ① bei entspanntem Kaumuske
- ② Haare etwas zur Seite gelegt
- ③ vor Haarsatz aufgesetzt
- ④ auf Arcus zygomaticus

Key:

- 1 = for a relaxed masticating muscle
- 2 = hair placed a little to the side
- 3 = taken in front of the hair line
- 4 = on the zygomatic arch

Fig 3.1 Position of the circumaural test points

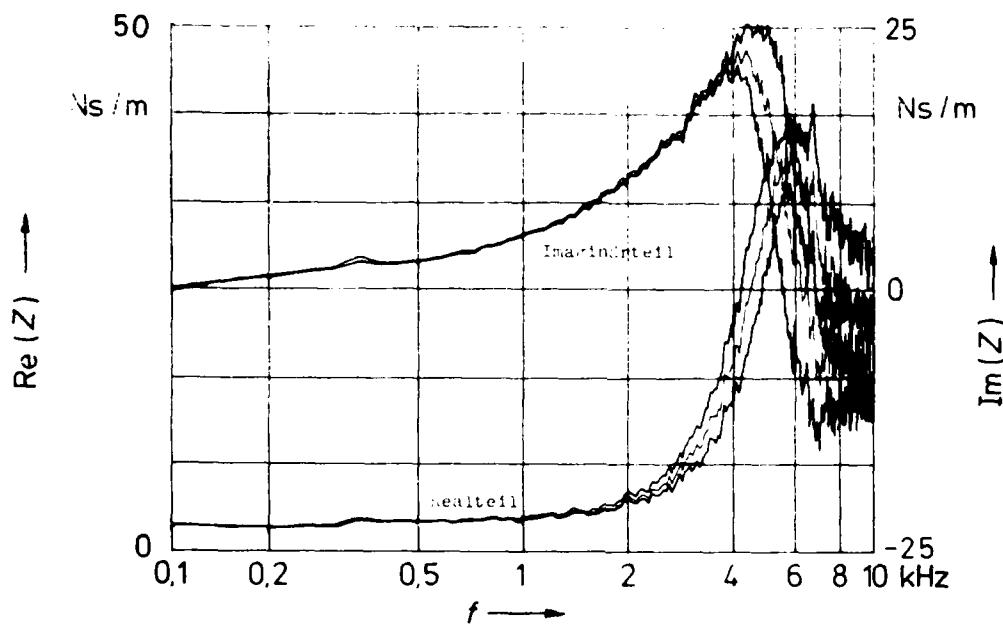
Fig 3.2



Top: female test persons
Centre: male test persons
Bottom: all test persons
Key:
Abscissa = class limits for age distribution

Fig 3.2 Age distribution for all test persons

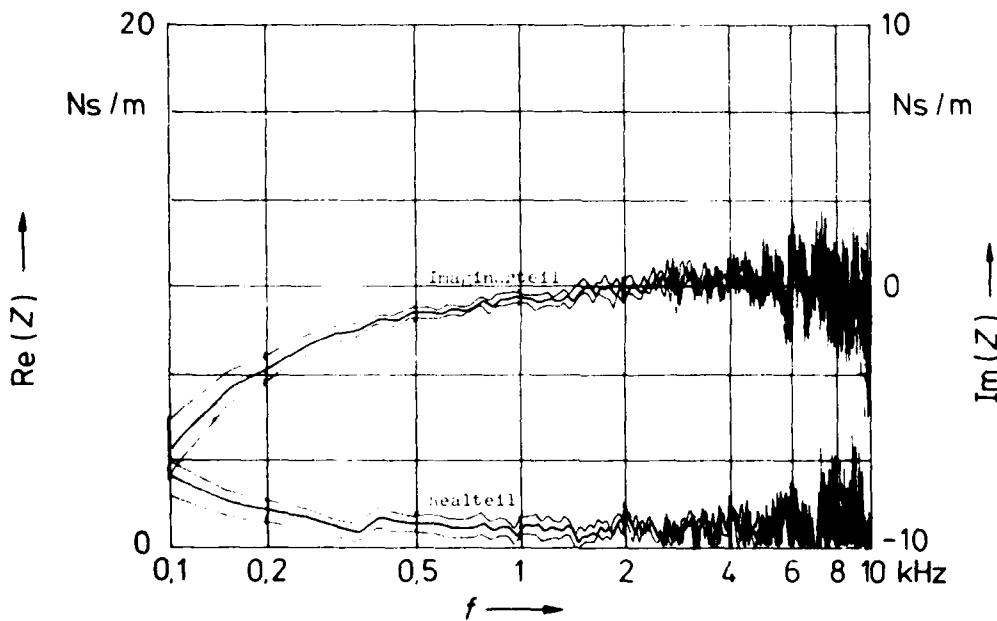
Figs 4.1 & 4.2



Key:

Imaginärteil = imaginary part
Realteil = real part

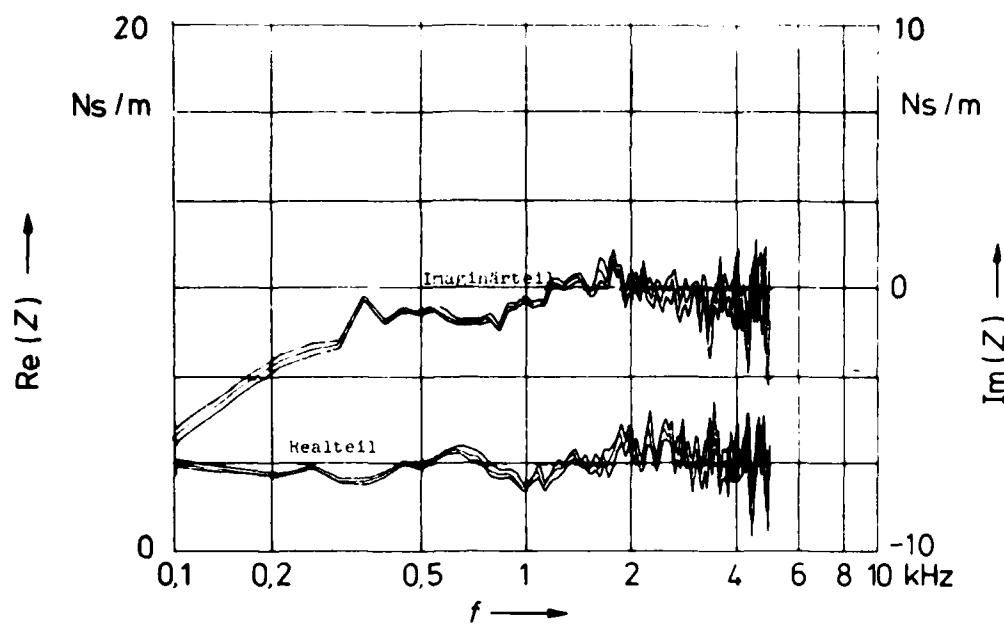
Fig 4.1 Mean value and standard deviation of impedance data for five measurements at test point 1, recorded for the same test person (static bearing force = 0.2N)



Key:

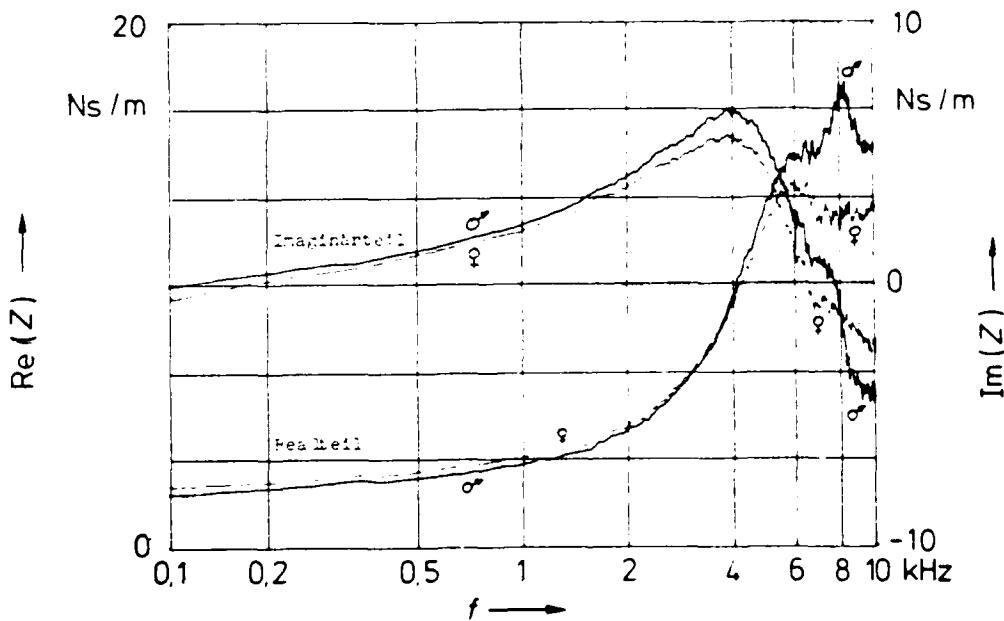
Imaginärteil = imaginary part
Realteil = real part

Fig 4.2 Mean value and standard deviation of impedance data for five measurements at test point 2, recorded for the same test person (static bearing force = 0.2N)



Key:
Imaginärteil = imaginary part
Realteil = real part

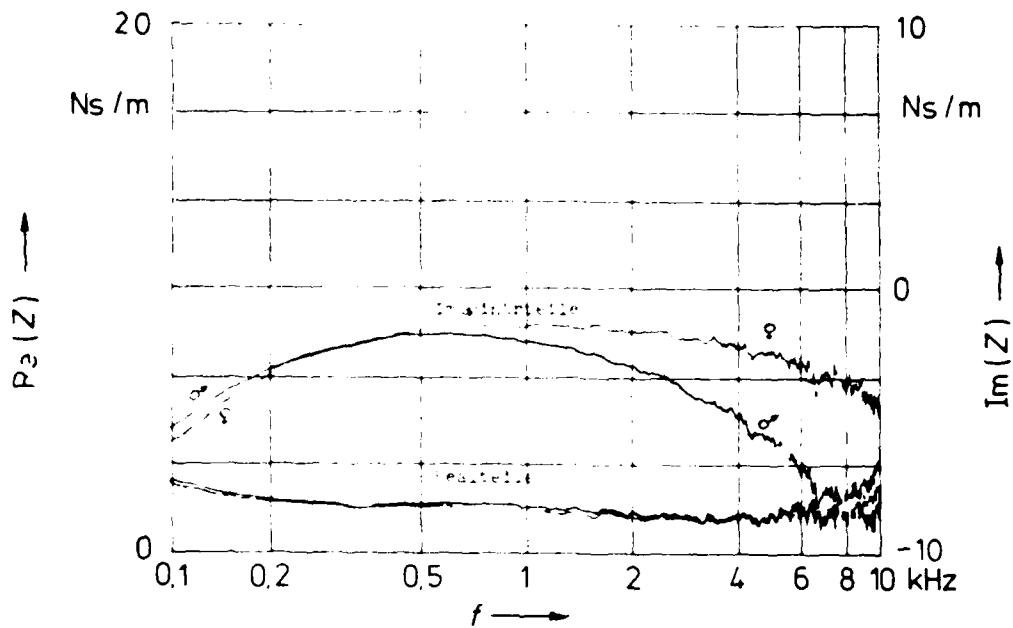
Fig 4.3 Mean value and standard deviation of the impedance of the wall of the auditory canal for five measurements recorded for the same test person



Key:
Imaginärteil = imaginary part
Realteil = real part

Fig 4.4 Mean values for male and female test persons;
 test point 1, 0.2N

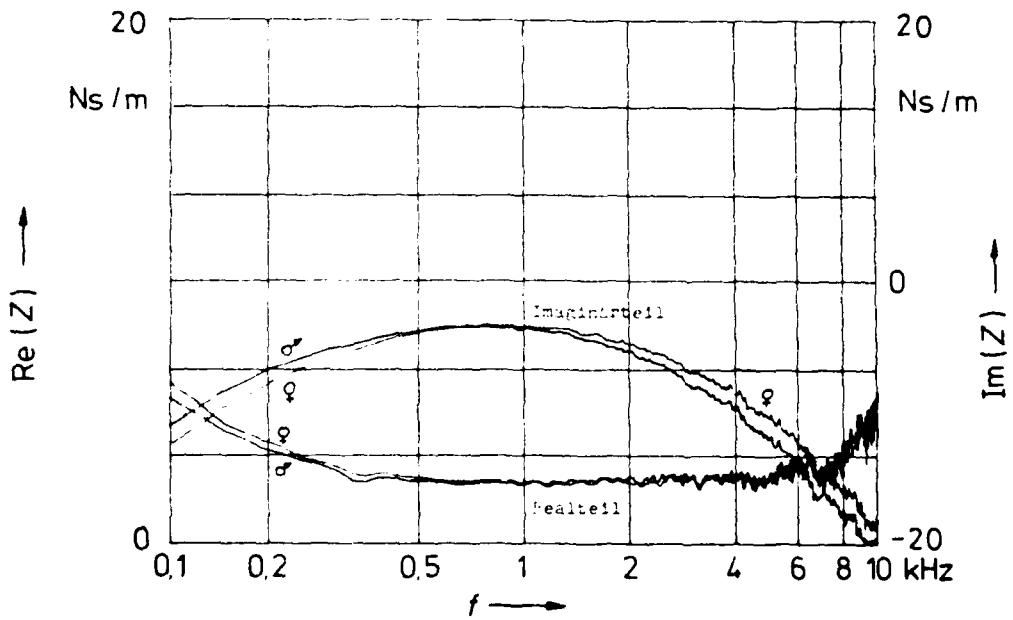
Figs 4.5 & 4.6



Key:

Imaginärteil = imaginary part
Realteil = real part

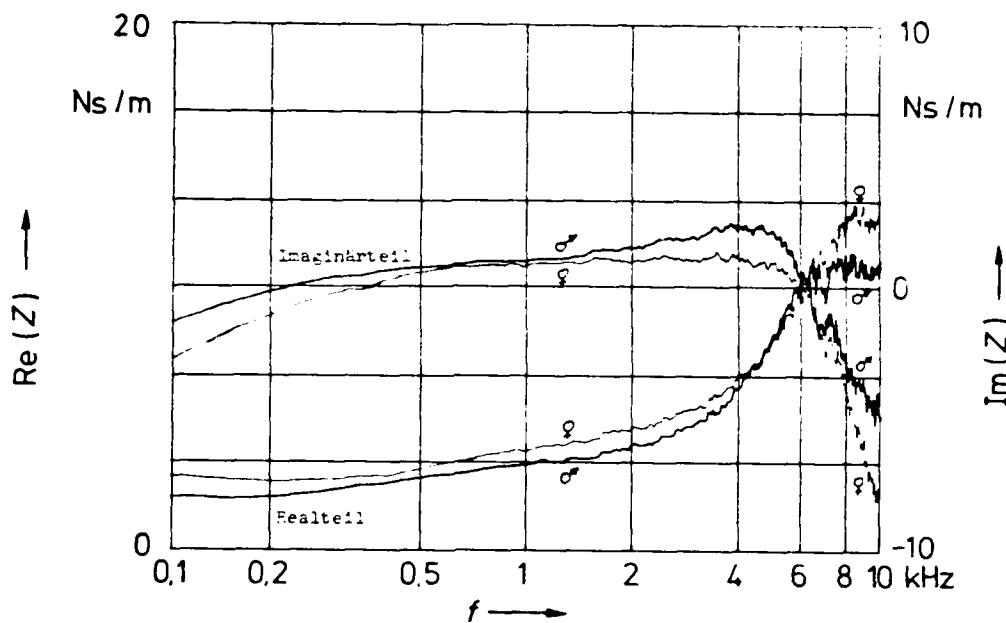
Fig 4.5 Mean values for male and female test persons;
test point 2, 0.2N



Key:

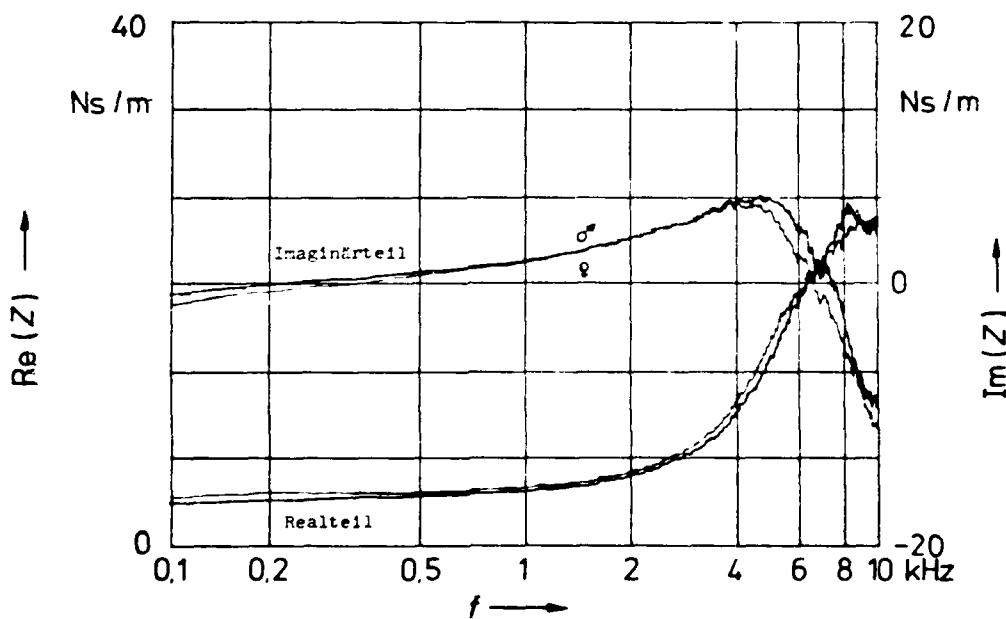
Imaginärteil = imaginary part
Realteil = real part

Fig 4.6 Mean values for male and female test persons;
test point 3, 0.2N



Key:
 Imaginärteil = imaginary part
 Realteil = real part

Fig 4.7 Mean values for male and female test persons;
 test point 4, 0.2N



Key:
 Imaginärteil = imaginary part
 Realteil = real part

Fig 4.8 Mean values for male and female test persons;
 test point 1, 0.5N

Figs 4.9 & 4.10

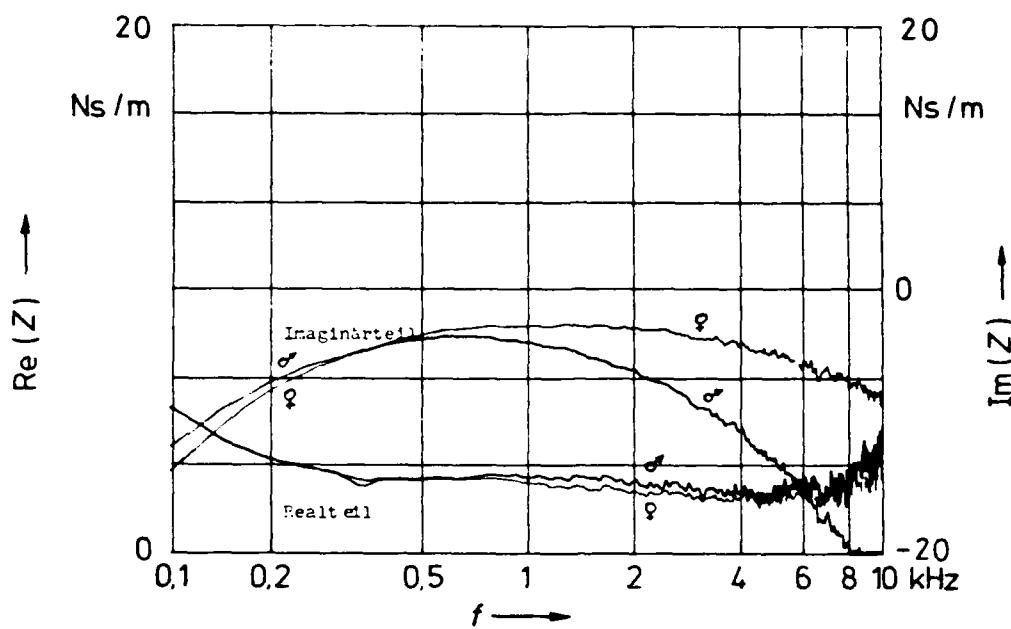


Fig 4.9 Mean values for male and female test persons;
 test point 2, 0.5N

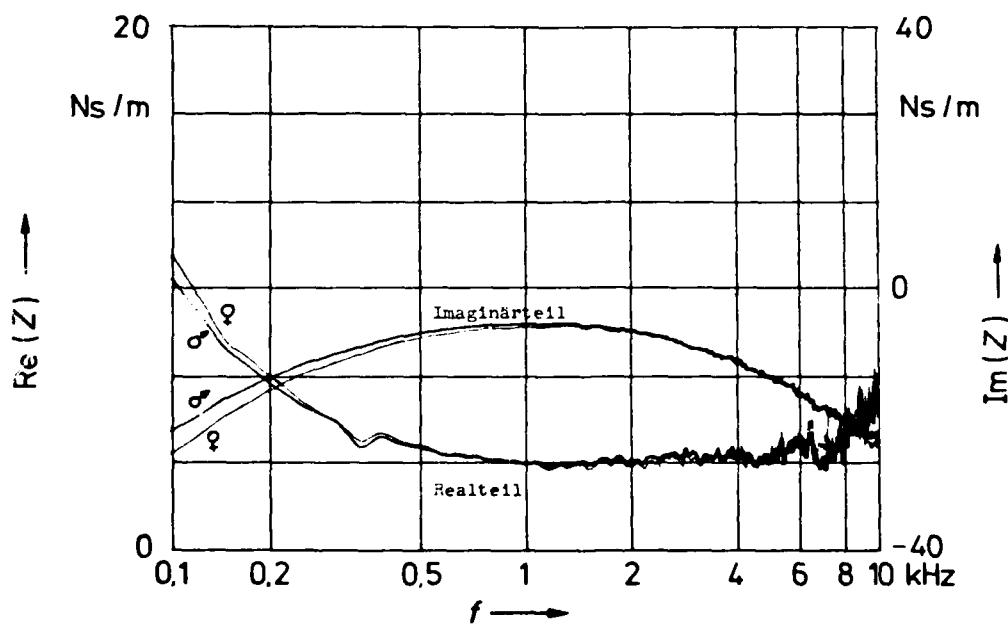
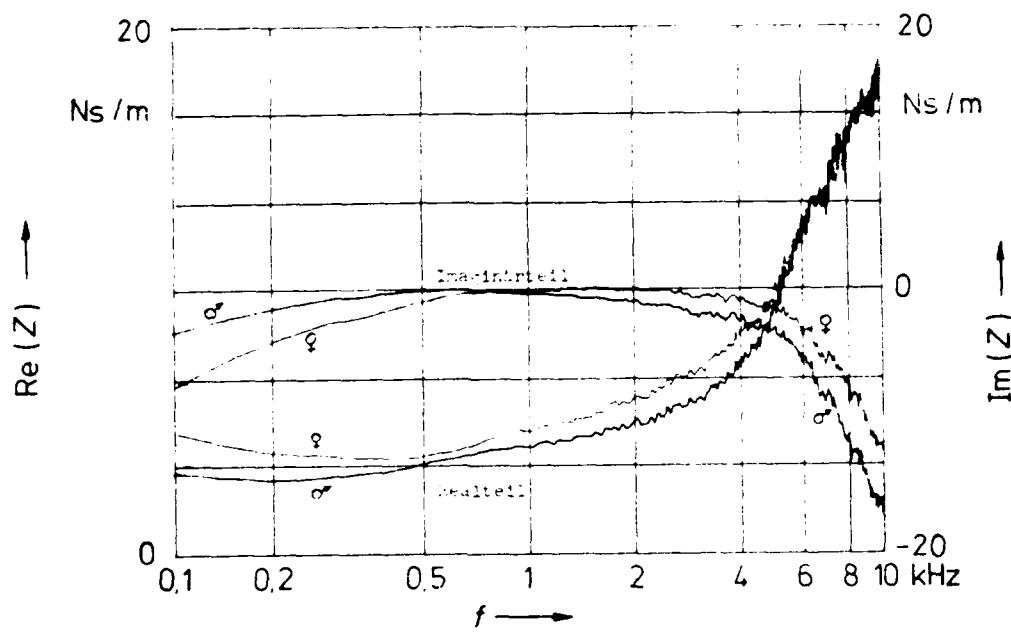
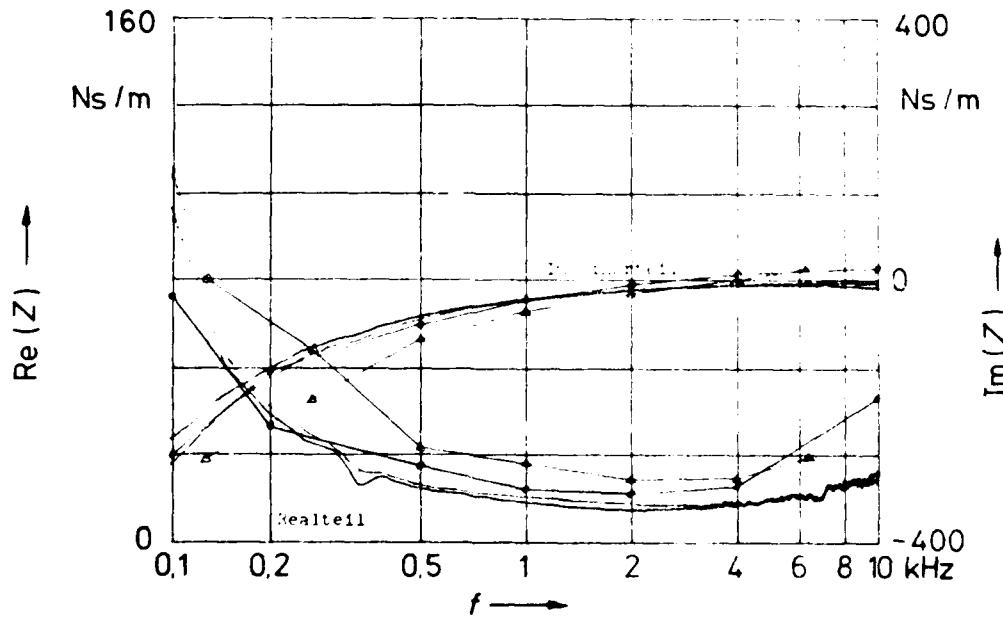


Fig 4.10 Mean values for male and female test persons;
 test point 3, 0.5N



Key:
 Imaginärteil = imaginary part
 Realteil = real part

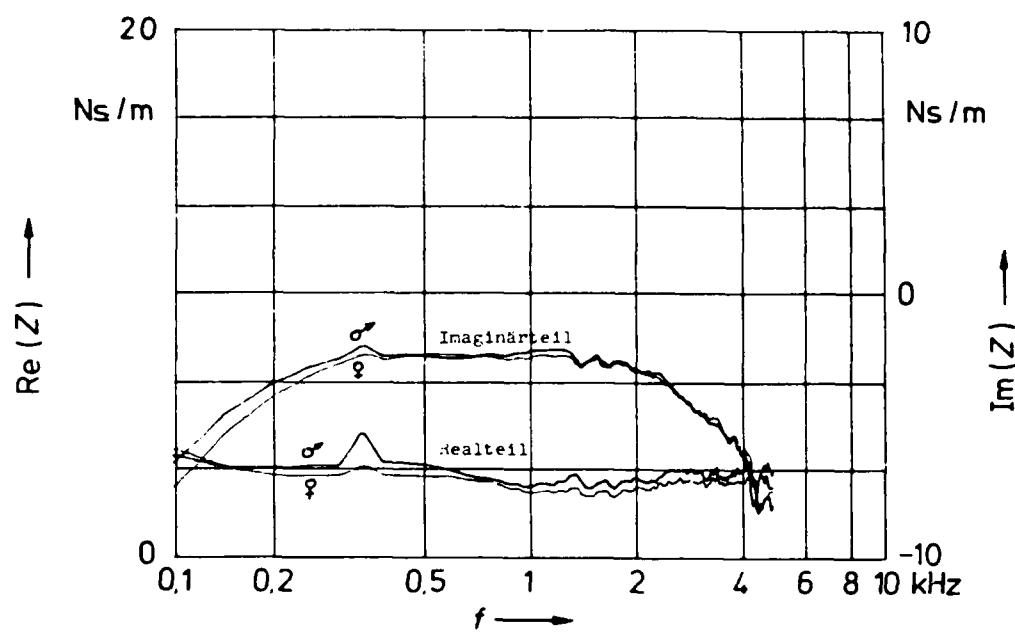
Fig 4.11 Mean values for male and female test persons;
 test point 4, 0.5N



Key:
 Imaginärteil = imaginary part
 Realteil = real part

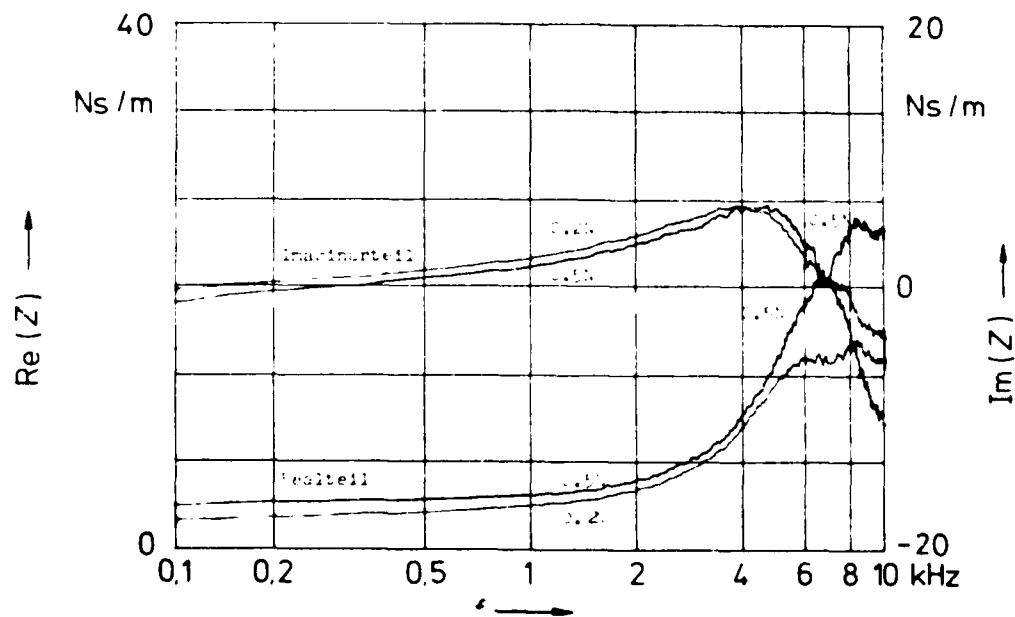
Fig 4.12 Mean values for male and female test persons;
 Results of other authors — Richter and Brinkmann,
 1973; — Flottorp and Solberg, 1976)
 test point 3, 5.4N

Figs 4.13 & 4.14



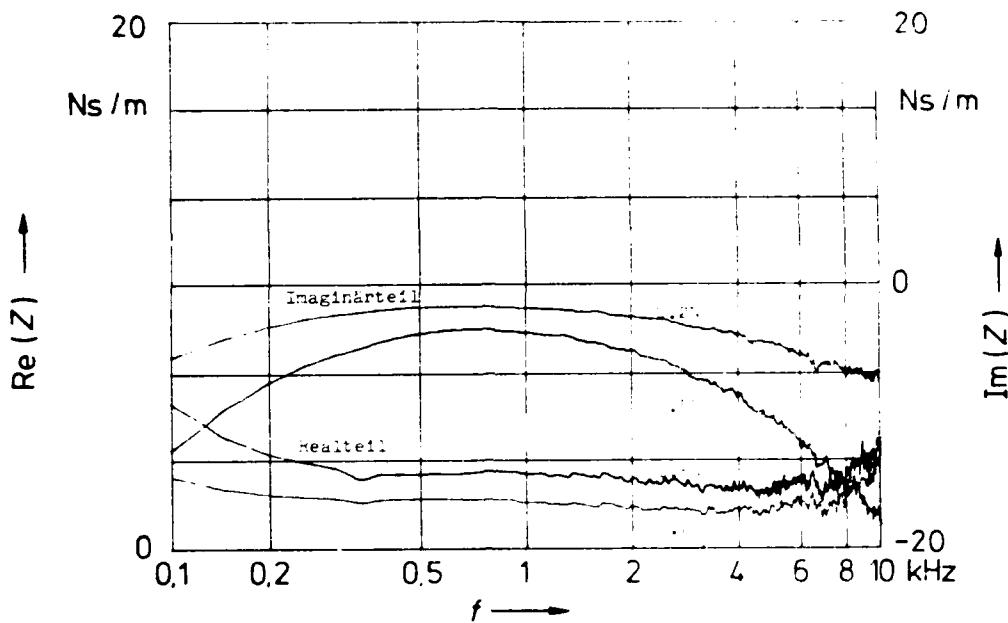
Key:
 Imaginärteil = imaginary part
 Realteil = real part

Fig 4.13 Mean values for male and female test persons;
 Impedance of the walls of the auditory canal



Key:
 Imaginärteil = imaginary part
 Realteil = real part

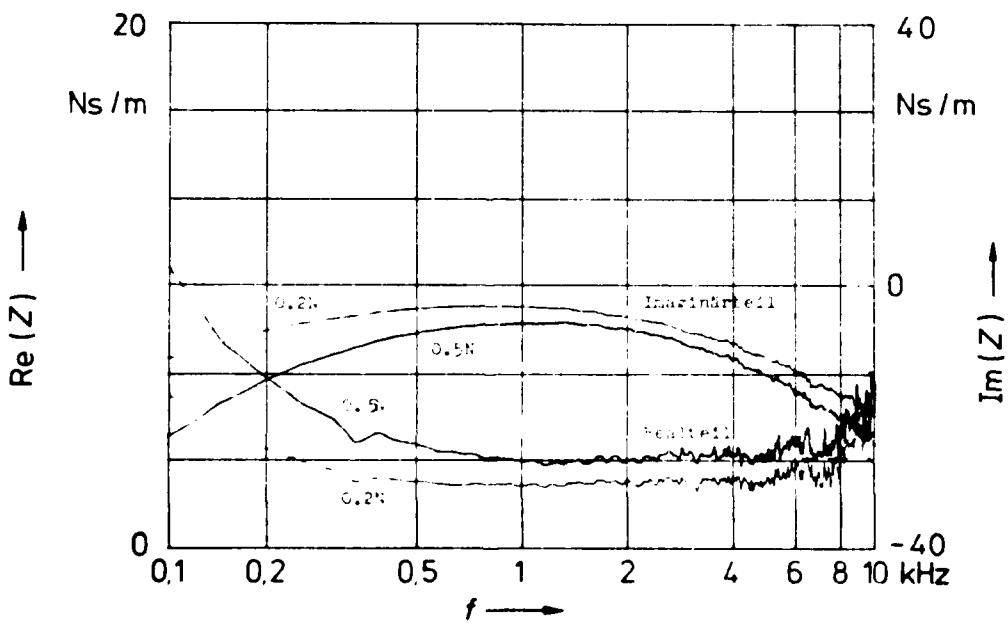
Fig 4.14 Mean values for all test persons and for both bearing forces;
 test point 1



Key:

Imaginärteil = imaginary part
Realteil = real part

Fig 4.15 Mean values for all test persons and for both bearing forces; test point 2

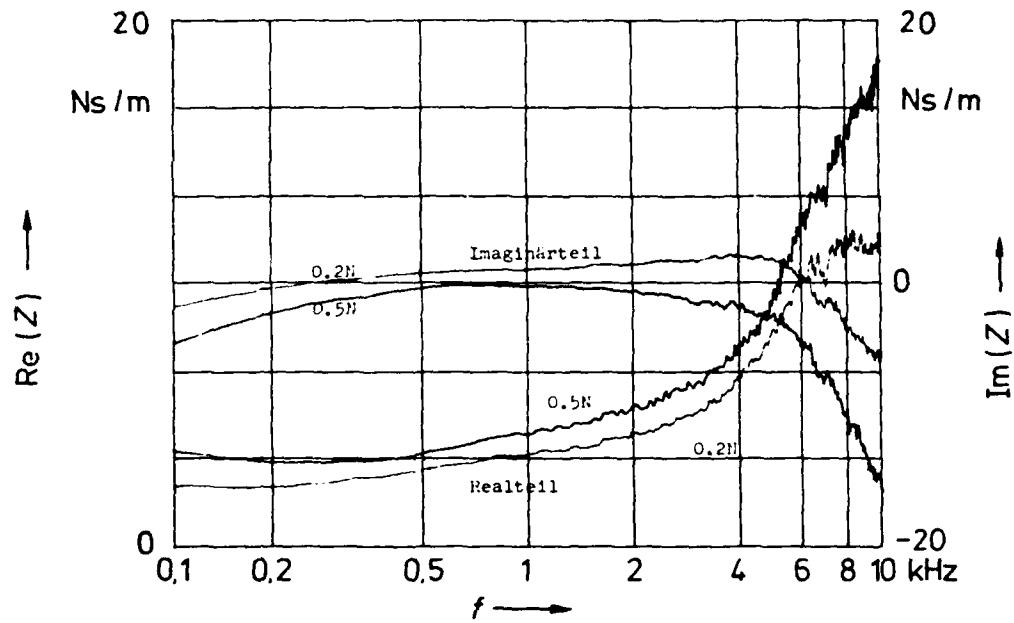


Key:

Imaginärteil = imaginary part
Realteil = real part

Fig 4.16 Mean values for all test persons and for both bearing forces; test point 3

Figs 4.17 & 4.18



Key:
Imaginärteil = imaginary part
Realteil = real part

Fig 4.17 Mean values for all test persons and for both bearing forces; test point 4

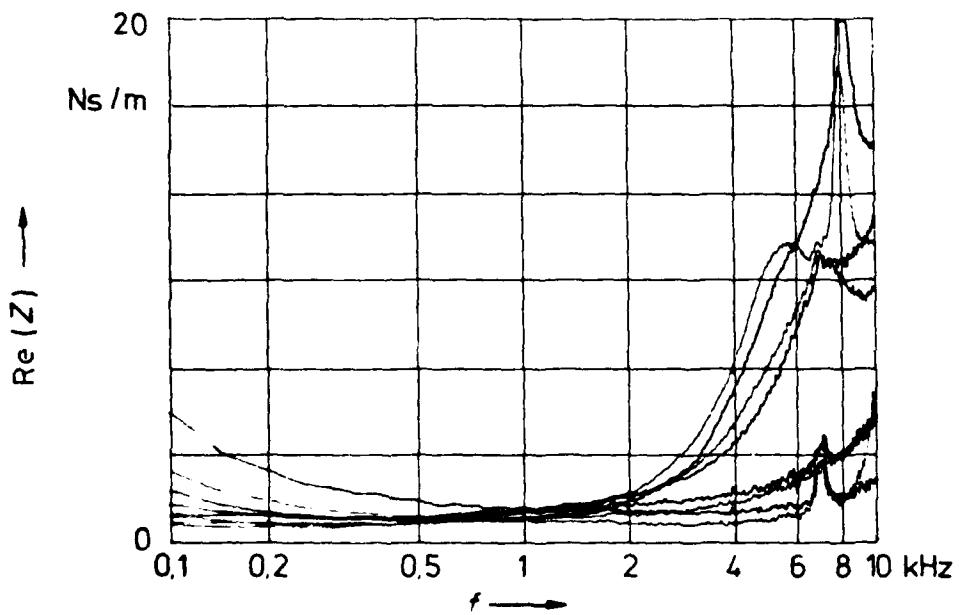


Fig 4.18 Standard deviation of the real part for data concerning all test persons (1 curve for each test point 1-4 and for each bearing force)

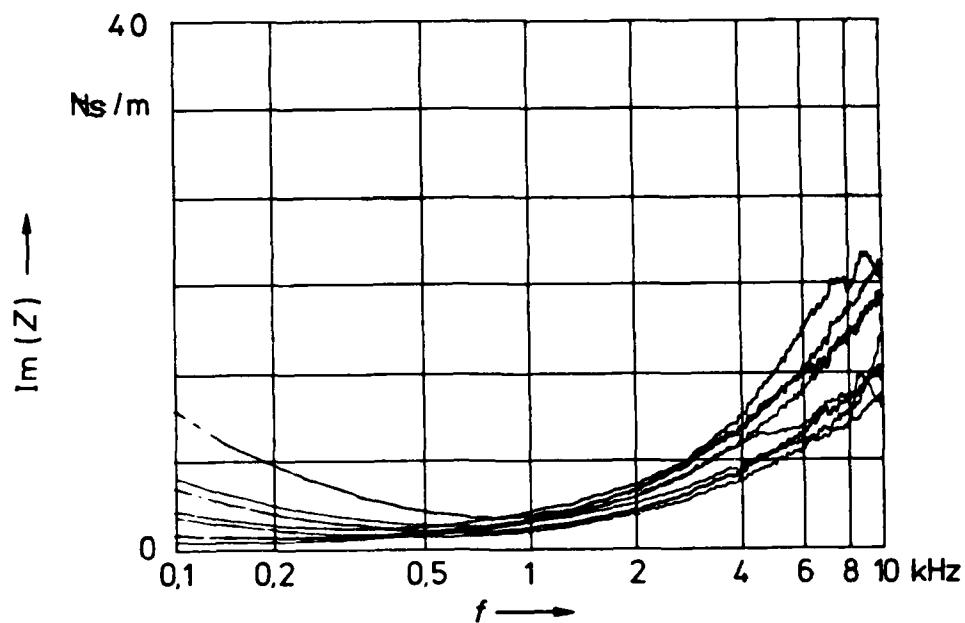
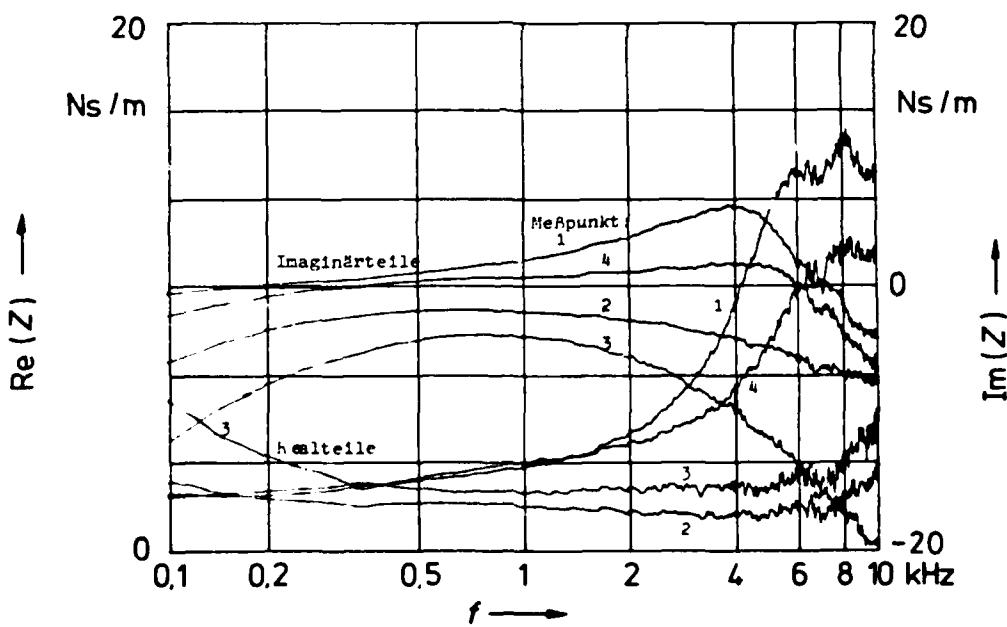


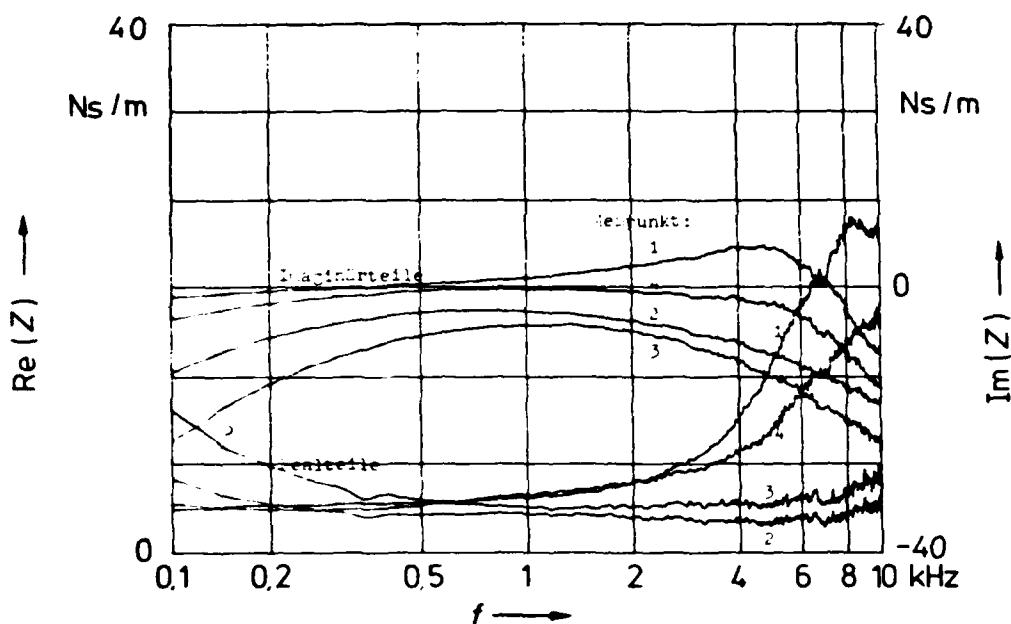
Fig 4.19 Standard deviation of the imaginary part for data concerning all test persons (1 curve for each test point 1-4 and for each bearing force)



Key:
 Imaginärteil = imaginary part
 Realteil = real part
 Messpunkt = test point

Fig 4.20 Mean values for all test persons and all test points; bearing force 0.2N

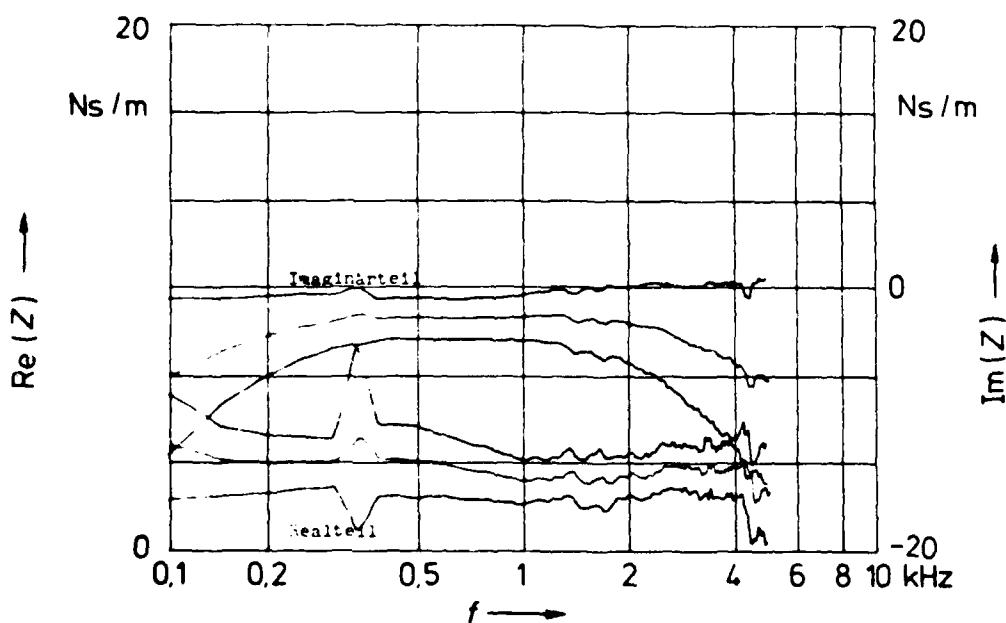
Figs 4.21 & 4.22



Key:

- Imaginärteil = imaginary part
- Realteil = real part
- Messpunkt = test point

Fig 4.21 Mean values for all test persons and all test points;
bearing force 0.5N



Key:

- Imaginärteil = imaginary part
- Realteil = real part

Fig 4.22 Mean value and standard deviation of the shearing
impedance of the wall of the auditory canal

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